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Topics on bar and bulge formation and evolution

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Abstract. I discuss results from the COSMOS survey, showing that the fraction of disc galaxies that is barred decreases considerably with look-back time from $z \sim 0.2$ to $z \sim 0.8$. This decrease is more important for small mass and low luminosity spirals. Classical bar formation theory provides a promising framework for understanding these results.

I also discuss the formation of discy bulges using N -body simulations reproducing well the properties of observed discy bulges. Thus, these simulated discy bulges have the shape of a disc, they have Sérsic profiles with small values of the shape index and their size is of the order of a kpc. They are formed by radial inflow of material driven by the bar and are thus composed of both gas and stars and have a considerable fraction of young stars. They can harbour spiral structure, or an inner bar.

1. Introduction

I will discuss two specific topics on bar and bulge formation and evolution. The first one concerns the formation of bars in time, measured from a large sample of disc galaxies observed with COSMOS. My collaborators for this work are Kartik Sheth, Debra Meloy Elmegreen, Bruce Elmegreen, Peter Capak, Roberto Abraham, Richard Ellis, Bahram Mobasher, Mara Salvato, Eva Schinnerer, Nick Scoville, Lori Spalsbury, Linda Strubbe, Marcella Carollo, Michael Rich and Andrew West. The second one discusses results of N -body simulations describing the formation of discy bulges. My collaborators for this work are Clayton Heller and Isaac Shlosman.

2. Evolution of the bar fraction in COSMOS: Quantifying the assembly of the Hubble sequence

Bars drive the angular momentum exchange between the various components of disc galaxies and therefore drive their evolution. When did they form? Where all bars formed at the same time, or not? Did specific types of barred galaxies form their bars before others? To answer questions such as the above, my collaborators and I analysed the fraction of disc galaxies that are barred in a large sample of galaxies from the COSMOS 2-square degree field (Scoville et al. 2007a,b). Setting thresholds for brightness, photometric accuracy, redshift, type and inclination angle, we obtain a sample of 2157 luminous, far from edge-on, spiral galaxies. Thus, our sample is an order of magnitude larger and is based on substantially deeper imaging data than other samples used in previous bar fraction investi-

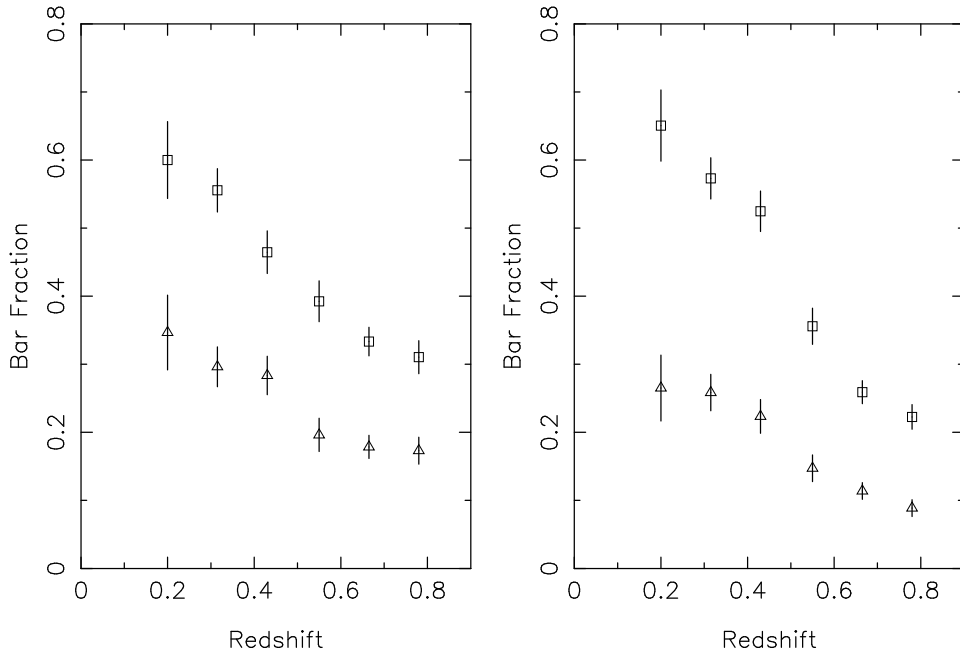


Figure 1. Fraction of disc galaxies that are barred (open squares), or strongly barred (open diamonds) as a function of redshift. The left panel gives results from the visual classification, while the right panel gives results from the classification based on the ellipse fits (see text). The error bars reflect the statistical uncertainty and are obtained from the expression $(f[1-f]/N)^{1/2}$, where f is the fraction and N is the number of galaxies.

gations (Abraham et al. 1999; Sheth et al. 2003; Elmegreen, Elmegreen & Hirst 2004; Jogee et al. 2004).

Each galaxy in our sample was analysed for the existence of a bar with two different methods and the results were cross-checked. For the first method we fitted ellipses on the isophotes of the galaxy images and identified bars from dual criteria on the profiles of the ellipticity and of the position angle of the ellipses. We also identified bars visually.

From this analysis we find that the fraction of disc galaxies which is barred is not constant with time, but increases strongly with decreasing redshift from $z = 0.84$ to $z = 0.2$. The size of our sample allows us to use six time bins and still have sufficient galaxies in each bin to reach statistically safe results. These results can be visualised in Fig. 1, where I show both the total fraction of bars and the fraction of strong bars. I also show separately the results from the visual classification (left panel) and the classification from ellipse fitting (right panel). Although the thresholds for strong bars and the threshold between barred and non-barred galaxies may differ somewhat between the two classifications, it is evident that the increase of the bar fraction with decreasing redshift is equally clear in both cases.

We also find that the bar fraction in spiral galaxies depends on the stellar mass. Thus, the bar fraction in very massive, luminous spirals is about constant out to $z \sim 0.84$, whereas for the low mass spirals it declines significantly with

increasing redshift beyond $z = 0.3$ (see Figures 2 and 3 in Sheth et al. 2007). This result is a signature of downsizing and is intimately connected with what we may call the dynamical maturity of discs.

The increase in the bar fraction with decreasing redshift from $z = 0.84$ to $z = 0.2$ can be understood within the framework of classical bar formation theory. N -body simulations have long suggested that bars form spontaneously in galactic discs, usually on relatively short dynamical timescales. There are, however, two ways of slowing this down. One is to increase the halo mass fraction within the disc radius, and the other is to heat up the disc (Athanasoula & Sellwood 1986; Athanasoula 2002, 2003). Although in many ways very different, both these effects allow to slow down the formation of the bar. Thus, the time it takes for an unbarred disc galaxy to become barred can vary widely. In cold, disc-dominated cases, the bar forms within a Gyr or less. Sufficiently hot discs embedded in very massive halos can stay unbarred several Gyrs. Such a delay might well explain the time evolution of barred galaxy fraction shown in Fig. 1. It could also explain the downsizing signature found here, for two reasons. Observations show that the halo-to-disc mass ratio is higher in low mass, low luminosity galaxies than in bright, massive galaxies (Bosma 2004; Kranz, Slyz & Rix 2003) so that bars are expected to grow later in the former, as we indeed find here. Furthermore, there are suggestions that the former are dynamically hotter than the latter (Kassin et al. 2007). Although this picture could be complicated by interactions, or eventually by bar dissolution, it can, nevertheless, provide a framework within which our results can be understood.

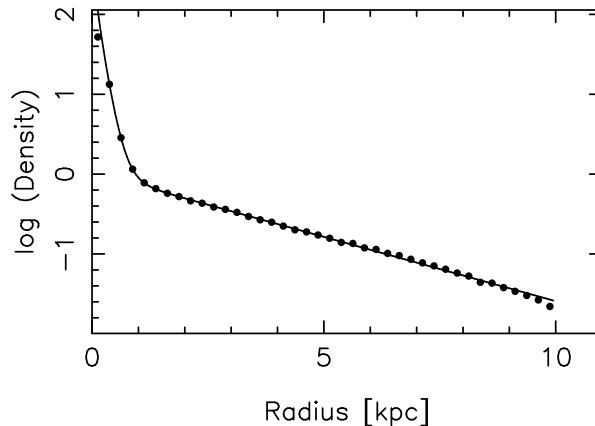
More discussion and analysis of these results can be found in Sheth et al. (2007).

3. Formation of discy bulges

Bulges are not a homogeneous class of objects, to a large extent due to the different definitions used so far. Athanasoula (2005) distinguished three different types of bulges : Classical, which resemble ellipticals in many ways; boxy/peanut bulges, which are just parts of bars seen near edge-on; and discy bulges, which are given the name ‘bulges’ because of their contributions to the inner parts of the radial luminosity profiles.

I present here results from simulations similar to those of Heller, Shlosman & Athanasoula (2007a) and (2007b), i.e. simulations including gas, stars and dark matter, as well as star formation, cooling and feedback. Several non-axisymmetric components – such as a triaxial halo, an oval disc, an inner and/or an outer bar – form during these simulations. Their interactions give very interesting dynamical phenomena (Heller et al. 2007a, b), while they induce considerable inflow and gaseous high density inner discs. This high gas concentration in the central area triggers considerable star formation, resulting in a disc-like central, high-density object, which, seen face-on, is often somewhat oval. It has many properties similar to those of discy-bulges. For example, it has, in many cases, sub-structures, like an inner bar. Furthermore, a decomposition of the stellar radial density profiles gives results in good agreement with observations. An example of such a radial projected surface density profile is given in Fig. 3., together with a fit by an exponential disc and a Sérsic component. Note that

Figure 2. Radial projected stellar density profile in arbitrary units. Radii are measured in kpc. The dots give the simulation results and the solid line the fit by an exponential disc and a Sérsic component.



the fit is excellent, all the way to the outer parts of the disc, roughly at 10 kpc. In this example, the disc scale-length is ~ 2.7 kpc, i.e. very realistic, while the Sérsic index is ~ 1 , in good agreement with observed discy bulges (see Kormendy & Kennicutt (2004) for a review).

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